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Stern Flap Performance on 110 ft Patrol Boat WPB1345 *STATEN ISLAND*

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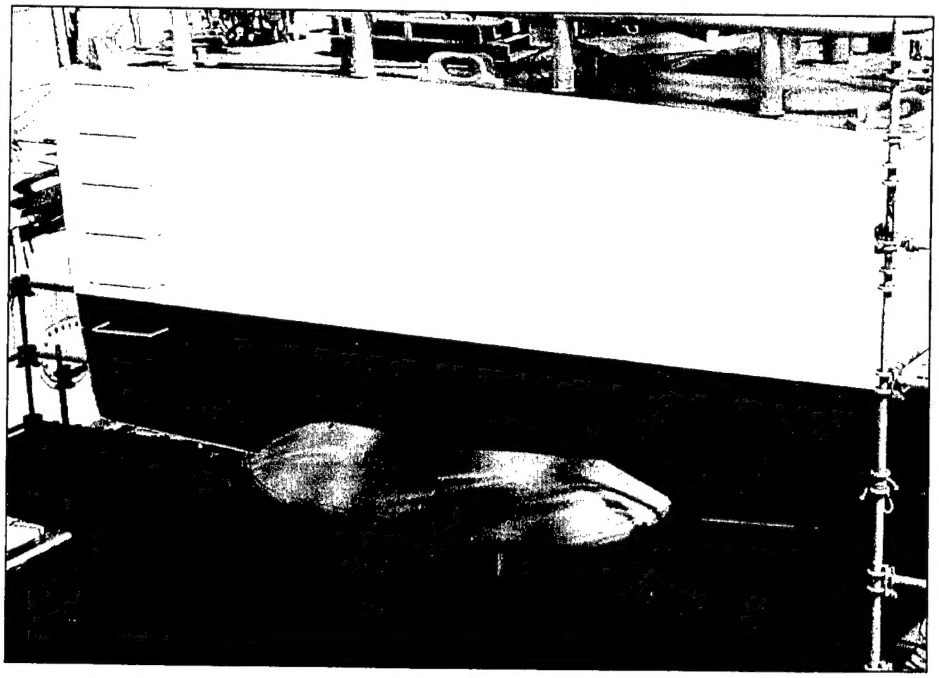

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The WPB1345 *STATEN ISLAND* was selected as a test ship for a full-scale at-sea evaluation of a stern flap design for the U.S. Coast Guard *ISLAND* Class (110 WPB) patrol boats. A baseline (pre-flap) speed trial was conducted. A stern flap was then installed, and a comparative post-flap speed trial was conducted. Adjustments were made to the data to account for differences in the loading conditions experienced during the two speed trials, and ship powering and fuel consumption were estimated.

Comparison of the pre- and post-flap trials performance indicated that the stern flap had the following benefits on the *ISLAND* Class:

- Shaft power reduction in the range of 4% to 19%, at equivalent ship speed.
- Top speed increased by 1.9 knots, due to the development of an additional 55 engine RPM and 168 hP at full power.
- Reduction in annual fuel consumption estimated to be 33,600 gallons (10.3%), with an associated fuel cost savings of $50,500/year.

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ABSTRACT

The WPB1345 *STATEN ISLAND* was selected as a test ship for a full-scale at-sea evaluation of a stern flap design for the U.S. Coast Guard *ISLAND* Class (110 WPB) patrol boats. A baseline (pre-flap) speed trial was conducted. A stern flap was then installed, and a comparative post-flap speed trial was conducted. Adjustments were made to the data to account for differences in the loading conditions experienced during the two speed trials, and ship powering and fuel consumption were estimated.

Comparison of the pre- and post-flap trials performance indicated that the stern flap had the following benefits on the *ISLAND* Class:

- Shaft power reduction in the range of 4% to 19%, at equivalent ship speed.
- Top speed increased by 1.9 knots, due to the development of an additional 55 engine RPM and 168 hP at full power.
- Reduction in annual fuel consumption estimated to be 33,600 gallons (10.3%), with an associated fuel cost savings of $50,500/year.

ADMINISTRATIVE INFORMATION

The ship trials were sponsored and conducted by the U.S. Coast Guard (USCG), Boat Engineering Branch (ELC-024). This document was prepared by Naval Surface Warfare Center, Carderock Division (NSWCCD), Resistance and Powering Department (Code 5200), Unit Order No. DTCG40-99-X-60002.

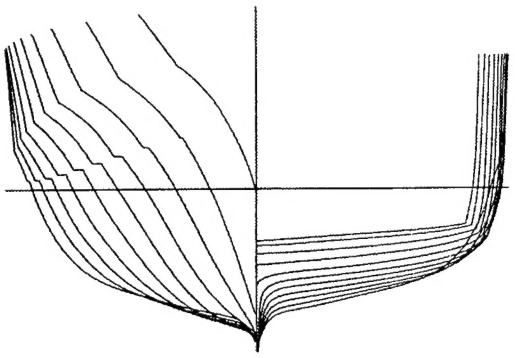
INTRODUCTION

The USCG *ISLAND* Class (110 WPB) patrol boats, with 49 units in active service, represents the largest class of cutters presently in the Coast Guard arsenal. The hull is a modified Vosper-Thornycroft (British) patrol boat design, 110 ft (33.5 m) in overall length, with twin shafts powered by twin diesel engines, and 49.6 inch (126 cm) diameter fixed-pitch propellers. Principal ship characteristics at full load, and a small-scale body plan of the hull, are presented as Table 1.

Ship trials on the *ISLAND* Class Series "C", of which there are eleven units, have indicated that their Caterpillar 3516 main engines operate above their recommended engine torque curve. This has resulted in the inability of this particular engine design to reach full engine RPM and power. In addition, long term operational experience on all *ISLAND* Class boats has shown propeller blade root erosion due to cavitation on the fleet propellers caused by excessive blade loading. Due to these problems, as well as others, the USCG initiated a program to improve the hydrodynamic performance of the *ISLAND* Class patrol boats [1].

Table 1. USCG *ISLAND* Class (110 WPB) principal ship characteristics

Length (LWL)	104.3 ft	31.8 m
Beam (Bx)	21.1 ft	6.4 m
Displacement	163.4 Lton	166.0 MT
Draft FP	7.66 ft	2.33 m
Draft AP	6.85 ft	2.09 m
Wetted Surface	2242 sqft	208.3 sqm
Coefficients:		
Cp = 0.691	Cb = 0.402	Cwp = 0.783



U.S. Navy experience with stern flaps has shown the potential for improvement in the speed and power characteristics of many ship types [2]. A stern flap is a small extension of the hull bottom surface aft of the transom. Stern flaps reduce the power required to propel the ship through the water, thereby reducing annual fuel consumption, while additionally increasing the ship's top speed. Model experiments were performed to design and select a stern flap for the *ISLAND* Class patrol boats [3]. The model-scale tests indicated that the installation of a stern flap could accomplish several of the *ISLAND* Class hydrodynamic program objectives, namely:

- Increase the maximum attainable speed at full power
- Reduce power-at-speed and propulsion fuel usage
- Better balance the ship's speed/power characteristics with the engine operating envelope

The length and displacement of the *ISLAND* Class represents the smallest platform to which this current technology has been applied. Also, this stern flap design represented the initial use of a greatly reduced span flap, and the initial design for a fully-planing craft.

The WPB1345 *STATEN ISLAND* was selected as a test ship for the full-scale at-sea stern flap evaluation. Baseline (pre-flap) speed trials on *STATEN ISLAND* were accomplished in July 2001. The stern flap was installed, during a dry-dock period of July-August 2001. Photographs of the completed stern flap installation on the *STATEN ISLAND* are shown as Figure 1. Speed trials were completed with the stern flap installed in August 2001. Comparisons are made between the *STATEN ISLAND* pre- and post-flap trials, and stern flap performance is determined both at the trials conditions, and for the *ISLAND* Class patrol boats, in general.

This document was assembled with the intention of reporting the data from the *STATEN ISLAND* stern flap evaluation trials with a minimum of analysis and discussion.

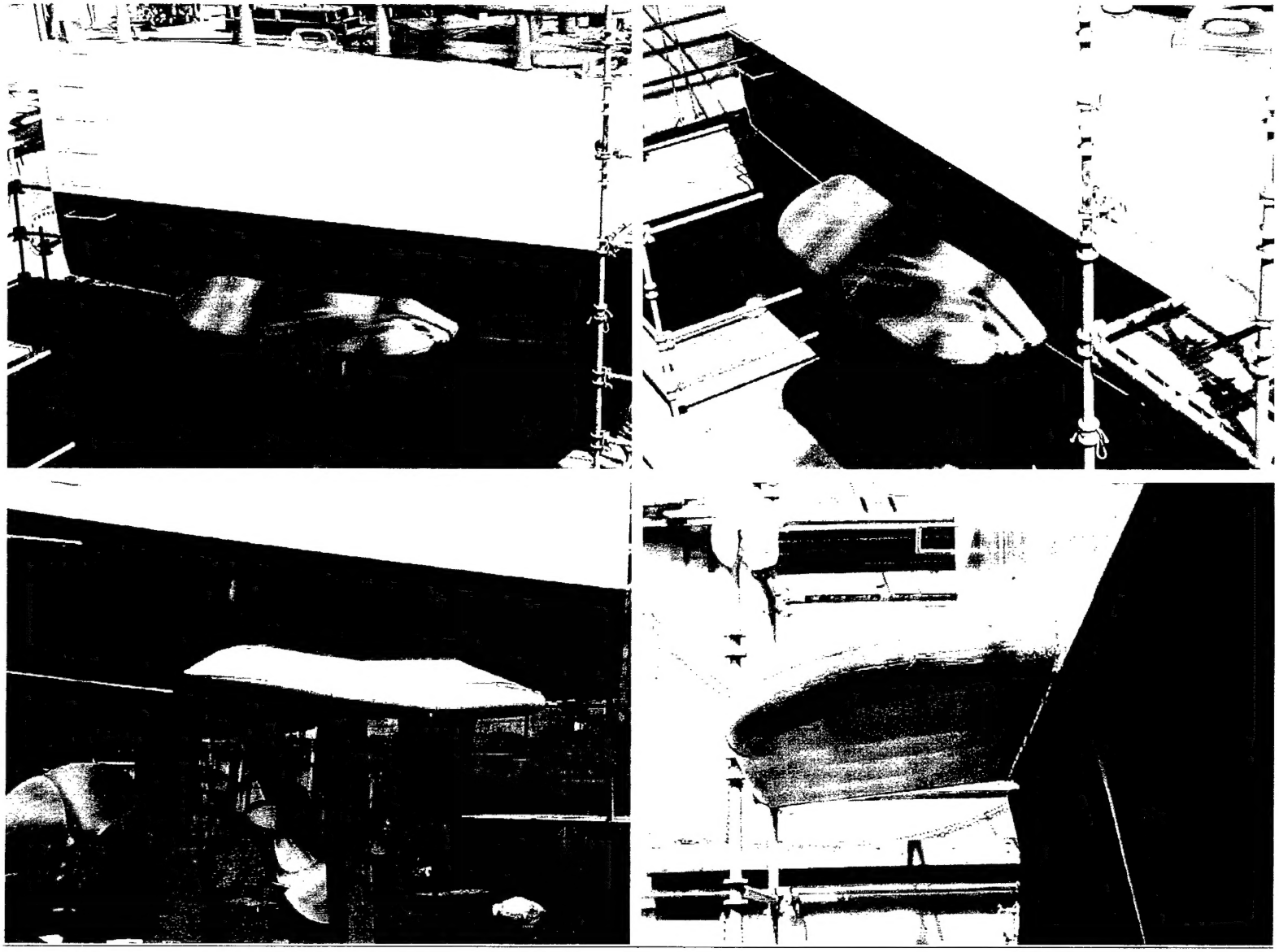


Fig. 1. Completed stern flap installation on WPB1345 *STATEN ISLAND*

STERN FLAP INSTALLATION ON STATEN ISLAND

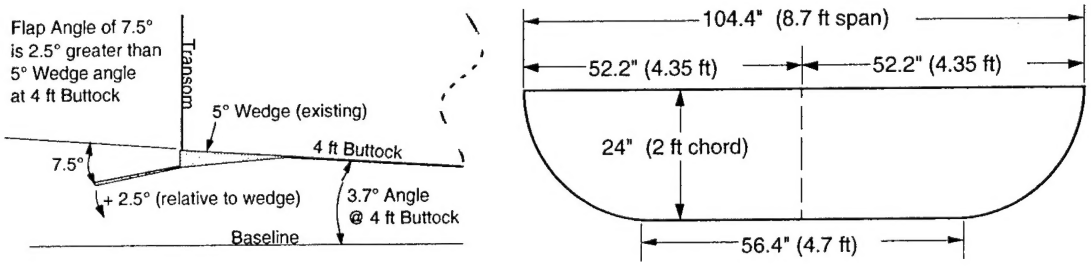
An initial prototype "first of series" stern flap was installed by the USCG on the on the WPB1340 *JEFFERSON ISLAND*, in Nov. 2000. The stern flap installation on the WPB1345 *STATEN ISLAND*, completed during a dry-dock period of July-August 2001, was the second prototype installation on the *ISLAND* Class.

The prototype stern flap installed on the *STATEN ISLAND* had associated costs of approximately $6,100 for "kit" manufacture, and about $7,500 for installation at a routine haul out (dry-dock) availability. The USCG is proceeding with plans to retrofit all *ISLAND* Class patrol boats with the stern flaps. The total procurement cost for the first batch of thirty-three *ISLAND* Class stern flap kits was $64,839, ($54,160 for manufacture and $10,679 for packaging). This corresponds to a stern flap kit per unit cost of $1,965. With shipping, the total stern flap retrofit cost at a routine availability is estimated to be on the order of $10,000. (Haul out fees are not included in the marginal costs as hauling is required for other routine purposes.) The non-recurring model test and stern flap design costs are less than $2,000 per boat.

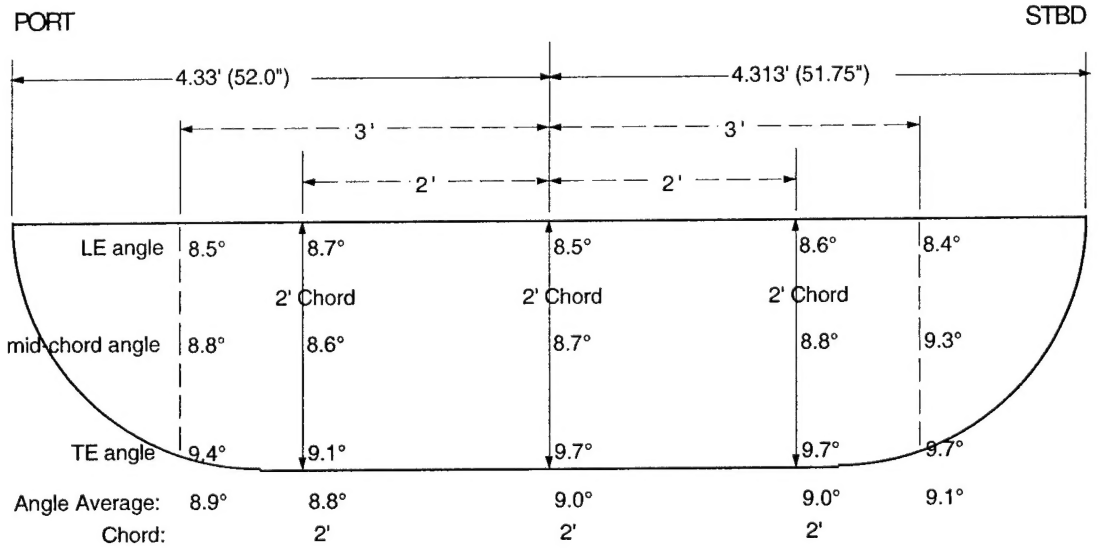
A series of measurements were obtained jointly by NSWCCD (5200) and USCG (ELC-024) representatives during a dry-dock inspection of the *STATEN ISLAND* stern flap, in August 2001. Definitions of stern flap geometry, and measurements on *STATEN ISLAND*, are presented in Figure 2. The stern flap measurements of chord and span were made with a steel tape measure (rule). Flap angle measurements were obtained from a digital angle indicator referenced (zeroed) longitudinally along the 4 ft (1.22 m) buttock reference points, port and starboard. The stern flap angle is defined with reference to the local run angle at the transom along the 4 ft (1.22 m) buttock because ship drawings specify the angle of the transom wedge (inlayed into the present hull design) to be 5° at this point. It was assumed that the wedge on the *STATEN ISLAND* was correctly manufactured at the stated 5° in order to obtain these measurements. In the defined coordinate system, the stern flap design angle of 7.5° would be 2.5° greater trailing edge down than this reference angle.

Measurements on the *STATEN ISLAND* indicated that flap chord length and span were determined to be within design specifications, in so far as the measurement accuracy allowed. The flap angle appears to vary from 8.4° to 9.7°, with an average angle of 9.0°. The flap angle, at all locations measured, appeared to increase when traversing from leading edge to trailing edge of the flap. It has been documented that full scale installation of stern flaps have, in

general, exhibited accuracy in the installed angle in the range of $\pm$ 2°. The design angle of the *ISLAND* Class stern flap was specified to be 7.5°, therefore, the average angle of 9.0° for the stern flap as installed on *STATEN ISLAND*, is 1.5° greater trailing edge down than designed. The model-scale data [3] indicates that the increased angle would tend to improve the powering performance of the stern flap at speeds of 15 knots and above. However, there will also be an increased loss of freeboard forward due to increased bow down trim moment.



USCG *ISLAND* (110' WPB) Class stern flap definitions and dimensions as designed



USCG *STATEN ISLAND* (WPB 1345) stern flap dimensions as measured

Fig. 2. Stern flap geometry and measurements on WPB1345 *STATEN ISLAND*

BASELINE AND STERN FLAP SPEED TRIALS

Due to budget and scheduling constraints, the USCG elected to conduct trials of very limited scope for the *ISLAND* Class stern flap evaluation. Pre- and post-flap "Speed Trials" on the *STATEN ISLAND* consisted of only ship speed measured through the Global Positioning System (GPS speed), from reciprocal runs, at selected nominal engine speeds of revolution (RPM). No measurements of shaft torque, or shaft power, were made.

It is typically very difficult to evaluate ship modifications on a full-scale basis, due to ship scheduling complications, and due to variation of parameters such as ship displacement, hull and propeller condition, and environmental conditions. In order to isolate the stern flap performance, best attempts were made to accomplish the baseline and stern flap trials with these conditions as similar as possible. The *STATEN ISLAND* speed trials were conducted under the direction of USCG Boat engineering Branch (ELC-024).

The *STATEN ISLAND* baseline speed trial was conducted on 11 July 2001. At the time of the baseline trial, the ship reported a 40 percent fuel and oil capacity (40% F/O) corresponding to a displacement of 137 L tons. The stern flap speed trial on *STATEN ISLAND* was conducted on 30 Aug 2001, at a reported 94% F/O capacity corresponding to a displacement of 157 L tons. This 20 ton greater displacement for the stern flap trial represents an increase of more than 14.5%. Comparisons of the speed trials data will be made as measured, baseline at 137 L tons versus stern flap installed at 157 L tons. However, final stern flap performance benefits on the *ISLAND* Class will be determined after accounting for the 14.5% displacement variation.

Prior to the baseline trial, divers inspected and cleaned the ship's hull and two propellers. The stern flap trial was conducted after less than one week out of dry-dock. Therefore, cleaning was not considered necessary. The *STATEN ISLAND* baseline and stern flap trials were conducted with an average sea state of 0-1, and true wind speeds of generally 35 knots an below. Pre- and post-flap trials were conducted in relatively the same body of water, at water depths in the range of 25 to 80 ft. The condition of the hull and propellers on *STATEN ISLAND*, and the encountered environmental conditions, are not considered to have adversely affected either trial.

The baseline and stern flap speed trials were structured in order to accurately define the *STATEN ISLAND* engine revolution to ship speed relationships, throughout the entire propulsion speed range of engine clutch to full power (nominally 10 to 28 knots). Reciprocal runs were accomplished at each condition tested, in order to eliminate the effects of water current, and thus

determine an accurate ship speed through the water. The uncertainty in the trials measurements were estimated to be $\pm$ 0.1 knots in the DGPS speed, and $\pm$ 3 engine RPM.

The speed trials data measured on the *STATEN ISLAND* in the baseline configuration (no stern flap), test date 11 July 2001, 40% F/O at 137 L tons, is presented in Table 2. The speed trials data measured on the *STATEN ISLAND* with the stern flap installed, test date 30 Aug 2001, 94% F/O at 157 L tons, is presented in Table 3. A comparison of the speed trials data as measured, baseline at 137 L tons versus stern flap installed at 157 L tons, is presented in Figure 3, and in Table 4 with the data interpolated to even increments of ship speed and engine revolutions (RPM). Even with the additional 20 tons displacement, the stern flap produced the following results during the *STATEN ISLAND* trials:

- ship speed increase at equivalent engine RPM throughout most of the engine envelope
- additional 80 engine RPM was developed at maximum engine setting, which resulted in a substantial increase of 1.4 knots in top speed

On a broad sense, the comparison of the *STATEN ISLAND* speed trials data as measured, Figure 3, exhibits nearly equivalent engine RPM - ship speed relationships for the 157 L tons stern flap case as that of 137 L tons baseline. In effect, one might conclude that the installation of the stern flap allowed for a ship with a 14.5% increase in displacement to have a performance similar to (and in fact slightly better) than that of the much lighter baseline hull.

No measurements of shaft torque or power were made during the *STATEN ISLAND* speed trials. Therefore, an attempt was made to estimate powering. Previous Class standardization trials were conducted on the WPB1343 *BAINBRIDGE ISLAND* [4]. Standardization trials powering data versus ship speed was obtained at both 137 L tons and 151 L tons. Data from these *BAINBRIDGE ISLAND* trials are presented in Appendix A, Table A1 and Figure A1, and compared to the main Caterpillar 3516 engine operating envelope in Figure A2.

For the baseline *STATEN ISLAND* speed trial, at 137 L tons, powering data was estimated by assuming the equivalent power versus engine revolutions characteristics from the *BAINBRIDGE ISLAND* trials conducted at the identical displacement. *STATEN ISLAND* with stern flap speed trial powering data was estimated by power versus engine revolutions characteristics from a linear extrapolation of the *BAINBRIDGE ISLAND* trials data to 157 L tons. Estimated *STATEN ISLAND* powering at trials conditions, baseline at 137 L tons versus stern flap installed at 157 L tons, are presented in Table 5, and referenced to the main Caterpillar 3516 engine operating envelope in Figure 4.

Table 2. WPB1345 *STATEN ISLAND* speed trials data for baseline without flap, 11 July 2001, at 137 L tons (40% F/O)

Staten Island test data 11 July 2001 without flap, 40% F/O at 137 L tons								
Nom'l RPM	DGPS Speed	Bridge RPM, P	Bridge RPM, S	Trim, + Bow Up	Wind Direction	Wind Speed	Water Depth	Compass Course
Clutch	10.1	680	664	0.4	80	18	28	210
Clutch	10.2	664	685	0.3	60	18	31	030
Clutch	**10.2**	**673**		**0.4**				
800	11.8	798	797	0.3	60	22	75	030
800	11.6	796	789	0.4	60	17	58	210
800	**11.7**	**795**		**0.4**				
900	13.1	904	900	0.4	60	20	45	210
900	12.9	903	898	0.5	45	18	50	030
900	**13.0**	**901**		**0.5**				
1100	15.0	1103	1097	1.4	50	22	80	210
1100	14.5	1106	1099	1.4	45	22	50	030
1100	**14.8**	**1101**		**1.4**				
1200	16.0	1200	1200	2.0	60	20	50	210
1200	15.4	1205	1192	2.0	60	20	50	030
1200	**15.7**	**1199**		**2.0**				
1500	21.0	1500	1500	3.0	45	25	30	190
1500	20.3	1492	1491	2.8	45	25	40	030
1500	**20.7**	**1496**		**2.9**				
1600	22.8	1610	1604	3.4	25	20	25	015
1600	24.3	1611	1605	3.2	40	20	60	210
1600	**23.6**	**1608**		**3.3**				
1700	26.5	1713	1709	3.0	40	25	35	210
1700	24.0	1688	1700	3.0	40	25	40	030
1700	**25.3**	**1703**		**3.0**				
Full	27.3	1796	1807	2.7	30	28	40	020
Full	28.7	1806	1812	2.3	30	23	30	210
Full (pre)	**28.0**	**1805**		**2.5**				

Table 3. WPB1345 *STATEN ISLAND* speed trials data with stern flap installed, 30 August 2001, at 157 L tons (94% F/O)

Staten Island test data 30 Aug 2001 with stern flap, 94% F/O at 157 L tons								
Nom'l RPM	DGPS Speed	Bridge RPM, P	Bridge RPM, S	Trim, + Bow Up	Wind Direction	Wind Speed	Water Depth	Compass Course
Clutch	9.4	685	685	-0.6	30 P	18	38	195
Clutch	11.0	685	685	-0.6	90 S	8	34	015
Clutch	**10.2**	**685**		**-0.6**				
800	12.7	803	798	-0.8	30 P	8	38	012
800	11.0	800	800	-0.6	30 P	18	40	194
800	12.5	800	800	-0.7	65 S	9	38	013
800	12.1	800		-0.7				
900	13.9	900	900	-0.4	80 S	8.5	36	013
900	12.5	898	900	-0.4	20 P	17	40	193
900	**13.2**	**900**		**-0.4**				
1100	14.3	1100	1100	0.0	20 P	18	39	193
1100	15.7	1098	1098	0.0	55 S	8	38	013
1100	**15.0**	**1099**		**0.0**				
1200	15.7	1210	1210	0.7	20 P	20	44	180
1200	16.6	1210	1210	0.4	60 S	7	40	005
1200	**16.2**	**1210**		**0.6**				
1500	20.1	1503	1502	2.0	2 P	21	47	190
1500	21.0	1499	1497	2.2	30 S	9	36	000
1500	**20.6**	**1500**		**2.1**				
1600	23.0	1598	1596	2.0	20 P	26	39	197
1600	23.5	1592	1596	2.0	30 S	7	44	000
1600	**23.3**	**1596**		**2.0**				
1700	25.6	1704	1701	1.3	20 P	32	34	205
1700	26.2	1707	1707	1.3	15 S	9	65	010
1700	25.6	1710	1710	1.3	5 P	30	64	190
1700	25.9	1707		1.3				
1800	27.4	1810	1810	2.0	12 P	35	70	197
1800	28.2	1810	1810	2.0	35 S	11	57	010
1800	**27.8**	**1810**		**2.0**				
Full	29.8	1880	1890	2.0	30 S	10	58	017
Full	29.0	1880	1890	2.0				
Full (post)	**29.4**	**1885**		**2.0**				

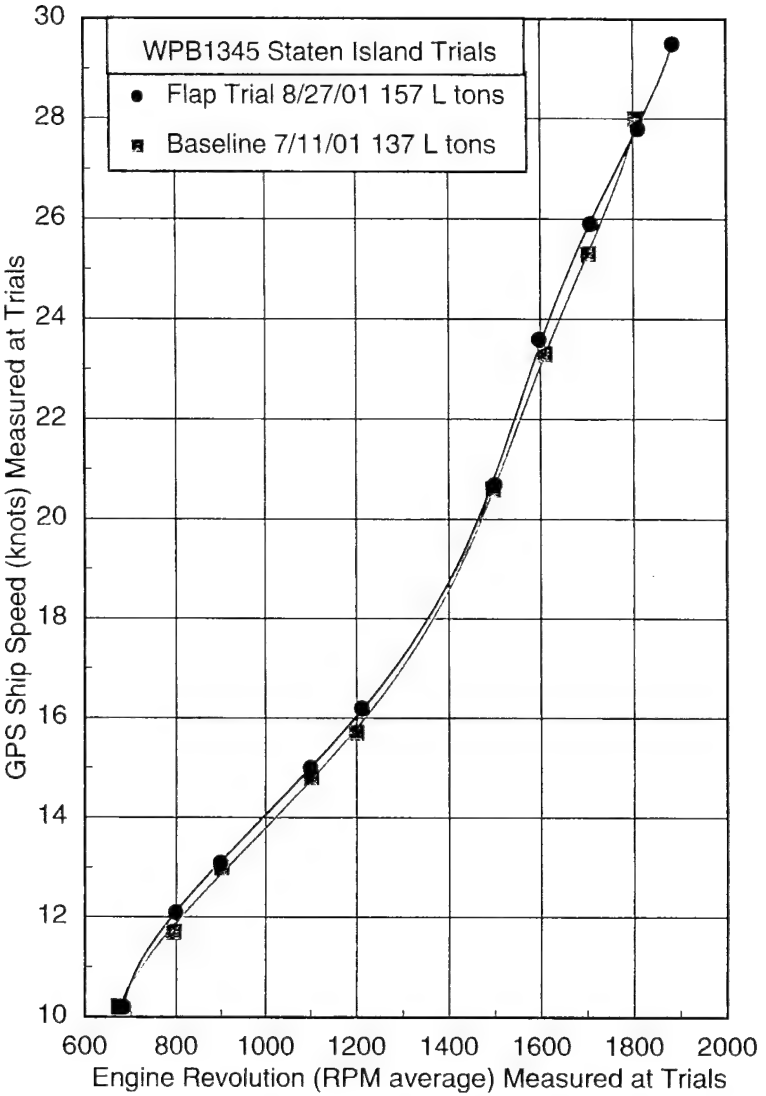


Fig. 3. WPB1345 *STATEN ISLAND* comparison of speed trials data as measured: baseline at 137 L tons versus stern flap installed at 157 L tons

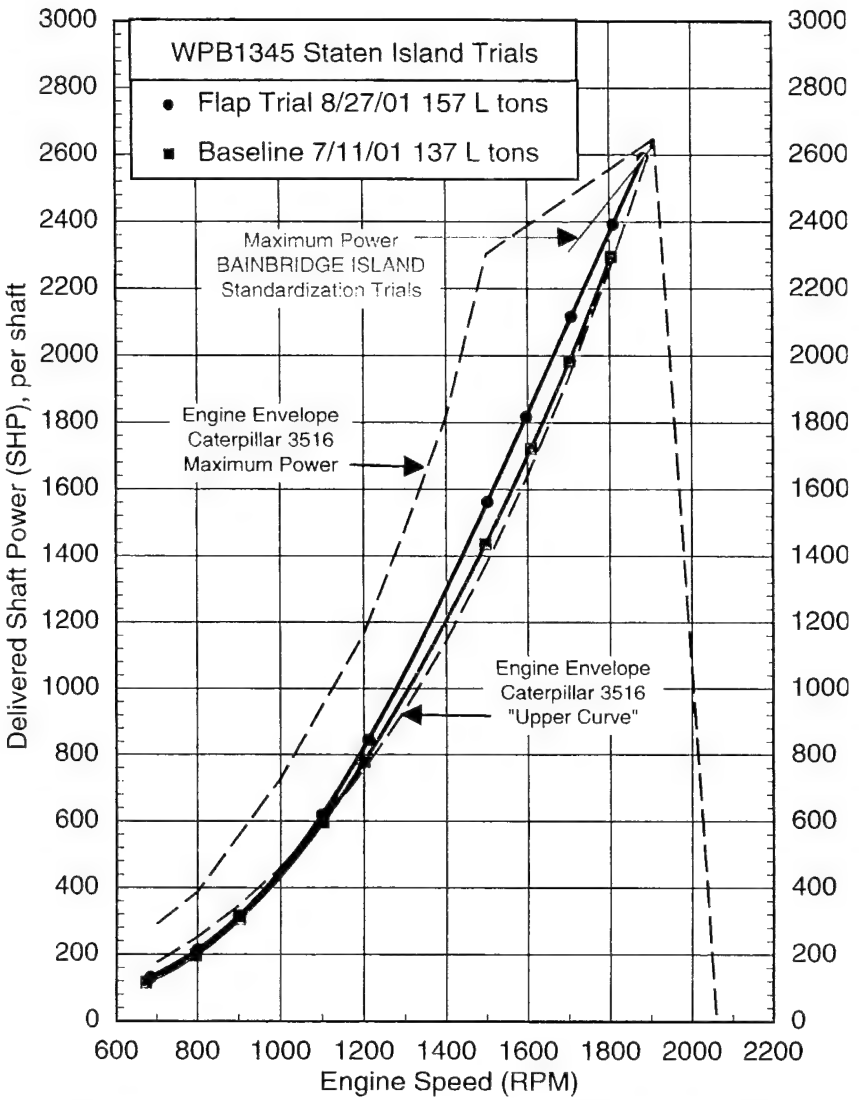


Fig. 4. WPB1345 *STATEN ISLAND* estimated powering at trials conditions, with reference to main engine operating envelope

Table 4. WPB1345 *STATEN ISLAND* comparison of speed trials data as measured: baseline at 137 L tons versus stern flap installed at 157 L tons, interpolated to even increments of ship speed and engine RPM

Comparison at Equivalent Engine RPM				Comparison at Equivalent Ship Speed			
Engine Revs (RPM)	Baseline, 137 L tons Speed (knots)	Stern Flap, 157 L tons Speed (knots)	Change in Speed (Δ knots)	Ship Speed (knots)	Baseline, 137 L tons Engine RPM	Stern Flap, 157 L tons Engine RPM	Change in Engine rev (Δ RPM)
680	10.28	10.20	-0.08	10.5	691	693	+2
700	10.59	10.49	-0.10	12	827	813	-14
800	11.89	12.09	+0.20	14	1020	995	-25
900	12.89	13.18	+0.29	16	1202	1175	-27
1000	13.78	14.05	+0.27	18	1357	1334	-23
1100	14.71	14.94	+0.23	20	1479	1463	-16
1200	15.81	16.02	+0.21	21	1528	1515	-13
1300	17.16	17.38	+0.22	22	1570	1561	-10
1400	18.80	19.08	+0.28	23	1607	1600	-7
1500	20.74	21.09	+0.35	24	1641	1636	-5
1600	22.94	23.33	+0.38	25	1675	1670	-5
1700	25.35	25.65	+0.30	26	1711	1705	-6
1800	27.86	27.84	-0.02	27	1755	1746	-9
1805	28.00	27.95	-0.05	28	1805	1796	-9
1885*	-	29.40	+1.40	29.4*	-	1885	+80

* Staten Island Baseline configuration did not attain this engine RPM or ship speed. Stern flap allows for an additional 80 engine RPM to be developed, resulting in the 1.4 knot speed increase.

Table 5. WPB1345 *STATEN ISLAND* baseline and stern flap installed, speed trials data with shaft power estimated from standardization trials data

STATEN ISLAND Baseline (without Flap)				STATEN ISLAND with Stern Flap Installed			
Staten Island Trials 11 July 2001 **baseline**, 40% F/O at 137 L tons		Shaft Power from Stnd. Trials on Bainbridge Island at 137 L tons. Values at Staten Island Engine RPM.		**Staten Island Trials** 30 Aug 2001 **with flap**, 94% F/O at 157 L tons		Shaft Power from Stnd. Trials on Bainbridge Island Estimated at 157 L tons. Values at Staten Island Engine RPM.	
Engine RPM avg	GPS Speed (Knots)	PD/Shaft (hP)	Total PD (hP)	Engine RPM avg	GPS Speed (Knots)	PD/Shaft Est (hP)	Total PD Est (hP)
673	10.2	116	232	685	10.2	132	264
795	11.7	198	396	800	12.1	215	430
901	13.0	306	612	900	13.2	316	632
1101	14.8	598	1196	1099	15.0	620	1240
1199	15.7	778	1556	1210	16.2	845	1691
1496	20.7	1435	2870	1500	20.6	1562	3124
1608	23.6	1721	3441	1596	23.3	1817	3634
1703	25.3	1983	3967	1707	25.9	2116	4231
1805	28.0	2295	4590	1810	27.8	2391	4782
				1885	29.4	2590	5180

ADJUSTMENTS FOR ACCURATE TRIALS COMPARISONS

Conditions existing at the time of the two *STATEN ISLAND* trials indicated that the baseline trial was conducted at a displacement and loading condition substantially lower than that of the stern flap trial. For the baseline speed trial, the lower displacement would bias the measured data towards higher ship speeds, when set at the specified conditions of engine revolutions. Consequently, lower shaft power would also be estimated. In order to isolate the effects of the stern flap on the ship's performance, the baseline and stern flap trials must be compared with conditions as similar as possible. An adjustment was made to the measured speeds for the *STATEN ISLAND* baseline trial, so that the final baseline data would be reflective of performance at the similar 157 L ton displacement as that of the stern flap trials.

The *ISLAND* Class standardization trials data, from the WPB1343 *BAINBRIDGE ISLAND*, was utilized to estimate the displacement-dependant speed adjustment. Standardization data at two displacements of 137 L tons and 151 L tons, allows for the determination of displacement effects on both speed/engine revolution relationship and speed/power performance, which was then applied to the *STATEN ISLAND* baseline trial data. The *STATEN ISLAND* baseline and stern flap speed trials data, with shaft power estimated from standardization trials data, and estimated speed loss and power increase due to 20 L ton displacement adjustment, is presented in Appendix A, Table A2. The authors feel the speed adjustment of the baseline trial will allow for a more accurate determination of the stern flap's speed/power performance.

STERN FLAP PERFORMANCE

The stern flap performance, as presented for the *STATEN ISLAND*, was determined once the effects of the displacement variation on the ship trials data was accounted for.

Effects on Speed/Power

A comparison of the baseline and stern flap trials on *STATEN ISLAND*, at 157 L tons, is summarized in Table 6 and Figures 5 through 7. A comparison at equivalent engine revolutions (RPM), the condition by which the speed trials were conducted, indicates that the stern flap will increase the ship speed by roughly 0.5 knots at engine clutch, increasing to 1.9 knots at full power. The trials show that the *STATEN ISLAND* with flap can maintain a higher ship speed for the same engine RPM, throughout the entire propulsion range of engine clutch through full power. At no point in the tested propulsion range did the stern flap induce a reduction in ship

speed. There is negligible change in delivered power at equivalent engine RPM, as the RPM-power relationships were both determined from the standardization trials data.

The trials comparison, when made at equivalent ship speed, indicates a stern flap power reduction of 10.9% at a ship speed of 10 knots, increasing to a maximum of 19% at 16 knots, and maintaining a power reduction up to the full power speed of the baseline configuration. The stern flap installation did not increase power at any ship speed.

Increase In Maximum Ship Speed

The maximum ship speed is defined as the speed attained when the maximum total rated shaft power (full shaft power) is developed. The full power per shaft rating of the *ISLAND* Class "C" series Caterpillar 3516 main engines is 2648 shaft horsepower (SHP) at 1910 RPM. This assumes a 3% gear loss from the rated 2730 brake horsepower (BHP). The *BAINBRIDGE ISLAND* standardization trials measured full power points of 2546 SHP at 1856 RPM for the 151 L ton trial and 2608 SHP at 1898 RPM for the 137 L ton trial, indicating a maximum of 2628 SHP at 1910 RPM. The *STATEN ISLAND* baseline and stern flap maximum speed, power, and engine RPM were estimated at the measured maximum power level indicated from the *BAINBRIDGE ISLAND* standardization trials, as depicted on Figure 6.

At the 157 L ton displacement, the maximum attainable ship speed for the baseline *STATEN ISLAND* is estimated to be 27.5 knots at a total delivered power of 5012 hP at 1830 engine RPM. With the stern flap installed, the maximum attainable speed is estimated as 29.4 knots at 5180 hP and 1885 RPM. The stern flap allows for an additional 55 engine RPM and 168 hP to be developed at full power, which results in an increase of 1.9 knots in top speed. (An increase of 1.4 knots was measured during the *STATEN ISLAND* speed trials.)

Comparison to Model-Scale Projection

A comparison of stern flap performance on *STATEN ISLAND*, to that of the model-scale projection from Reference 3, is presented in Figure 8. For a more accurate comparison to the full-scale 9° flap, the model-scale performance presented is for the selected flap at an angle of 10°, rather than the design 7.5°. As has been the case for all previous stern flap designs, the full-scale performance was better than that projected from the model-scale data, with the most significant differences being at the lower speeds.

Table 6. WPB1345 *STATEN ISLAND* baseline and stern flap installed, comparison of trials data at equivalent 157 L tons, interpolated to even increments of ship speed and engine RPM

Comparison at Equivalent Ship Speed*	Power and Engine RPM Decreases with Stern Flap Installed								
	Baseline (No Flap)			Stern Flap Installed					
Ship Speed	Engine Revolutions	Delivered Power/Shaft	Total Power	Engine Revolutions	Delivered Power/Shaft	Total Power	Change in Engine Revs	Change in Power	Change in Power
(knots)	(RPM)	(hP)	(hP)	(RPM)	(hP)	(hP)	(Δ RPM)	(Δ hP)	(%)
10	705	150	300	684	134	267	-21	-33	-10.9
12	859	255	510	812	220	440	-47	-70	-13.7
14	1076	570	1140	1002	475	950	-74	-190	-16.7
16	1293	1023	2047	1195	829	1657	-99	-390	-19.0
18	1446	1389	2778	1357	1219	2439	-88	-339	-12.2
20	1538	1705	3411	1470	1529	3059	-68	-352	-10.3
21	1587	1844	3687	1513	1647	3293	-74	-394	-10.7
22	1632	1969	3939	1551	1746	3491	-81	-447	-11.4
23	1675	2084	4169	1587	1838	3675	-88	-493	-11.8
24	1717	2190	4380	1625	1935	3870	-92	-510	-11.6
25	1755	2287	4575	1667	2048	4096	-89	-478	-10.5
26	1788	2377	4753	1713	2183	4366	-74	-387	-8.1
27	1809	2457	4915	1765	2335	4670	-44	-245	-5.0
27.5	1830	2506	5012	1791	2411	4822	-39	-190	-3.8
29.4	-	-	-	1885	2590	5180	+55	+168	+3.4

*Interpolated from Figure 7. Stern flap 1.9 knot speed increase results from development of additional 55 engine RPM and 168 hP.

Comparison at Equivalent Engine Revolutions**	Speed Increases with Stern Flap Installed								
	Baseline (No Flap)			Stern Flap Installed					
Engine Revolutions	Ship Speed	Delivered Power/Shaft	Total Power	Ship Speed	Delivered Power/Shaft	Total Power	Change in Speed	Change in Power	Change in Power
(RPM)	(knots)	(hP)	(hP)	(knots)	(hP)	(hP)	(Δ knots)	(Δ hP)	(%)
700	9.9	145	290	10.5	143	287	+0.6	-3	-1.0
800	11.1	219	439	12.1	218	436	+1.0	-2	-0.5
900	12.3	325	650	13.2	326	652	+0.9	+2	+0.4
1000	13.3	465	930	14.2	467	933	+0.8	+3	+0.4
1100	14.1	639	1277	15.0	641	1283	+0.9	+6	+0.4
1200	14.9	846	1691	16.0	843	1685	+1.1	-6	-0.4
1300	16.0	1080	2160	17.3	1071	2142	+1.2	-18	-0.8
1400	17.5	1334	2668	18.9	1324	2649	+1.4	-20	-0.7
1500	19.3	1602	3203	20.9	1597	3194	+1.6	-9	-0.3
1600	21.2	1876	3752	23.2	1879	3759	+1.9	+6	+0.2
1700	23.7	2152	4303	25.6	2159	4319	+1.9	+16	+0.4
1800	26.6	2426	4852	27.8	2417	4833	+1.3	-19	-0.4
1830	27.5	2506	5012	28.4	2485	4970	+0.9	-42	-0.8
1885	-	-	-	29.4	2590	5180	+1.9	+168	+3.4

**Interpolated from Figure 6. Stern flap 1.9 knot speed increase results from development of additional 55 engine RPM and 168 hP.

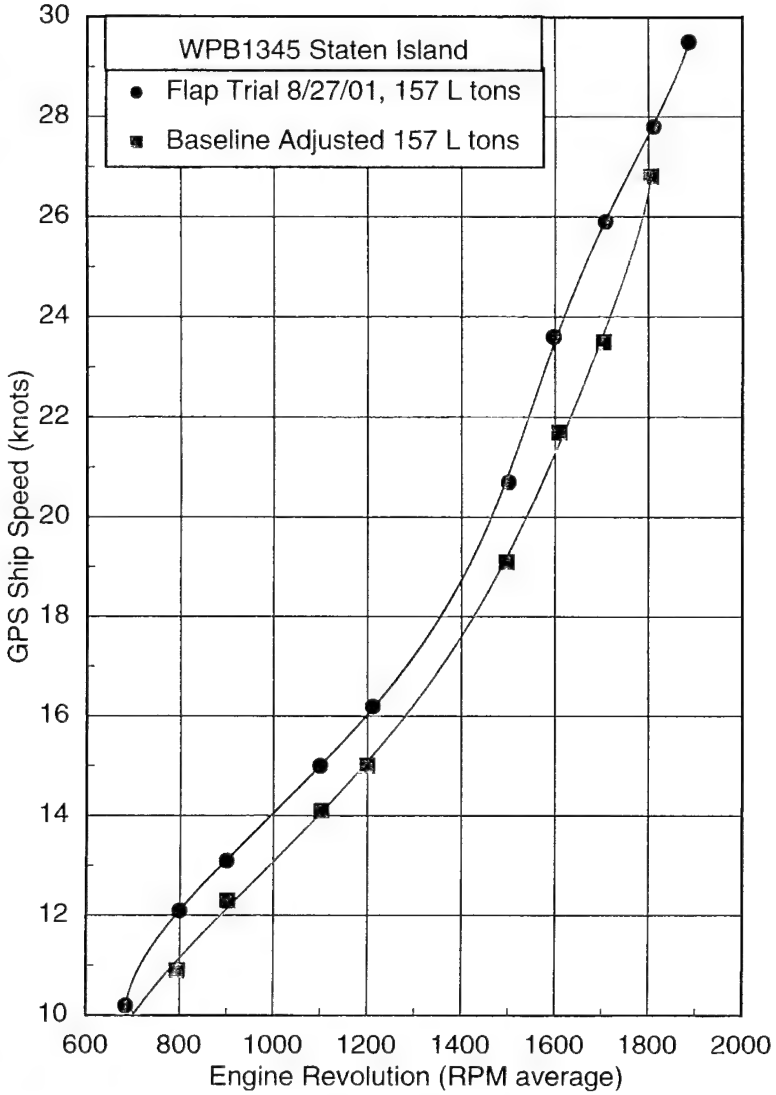


Fig. 5. WPB1345 *STATEN ISLAND* baseline and stern flap installed, speed trials data adjusted to equivalent displacement of 157 L tons

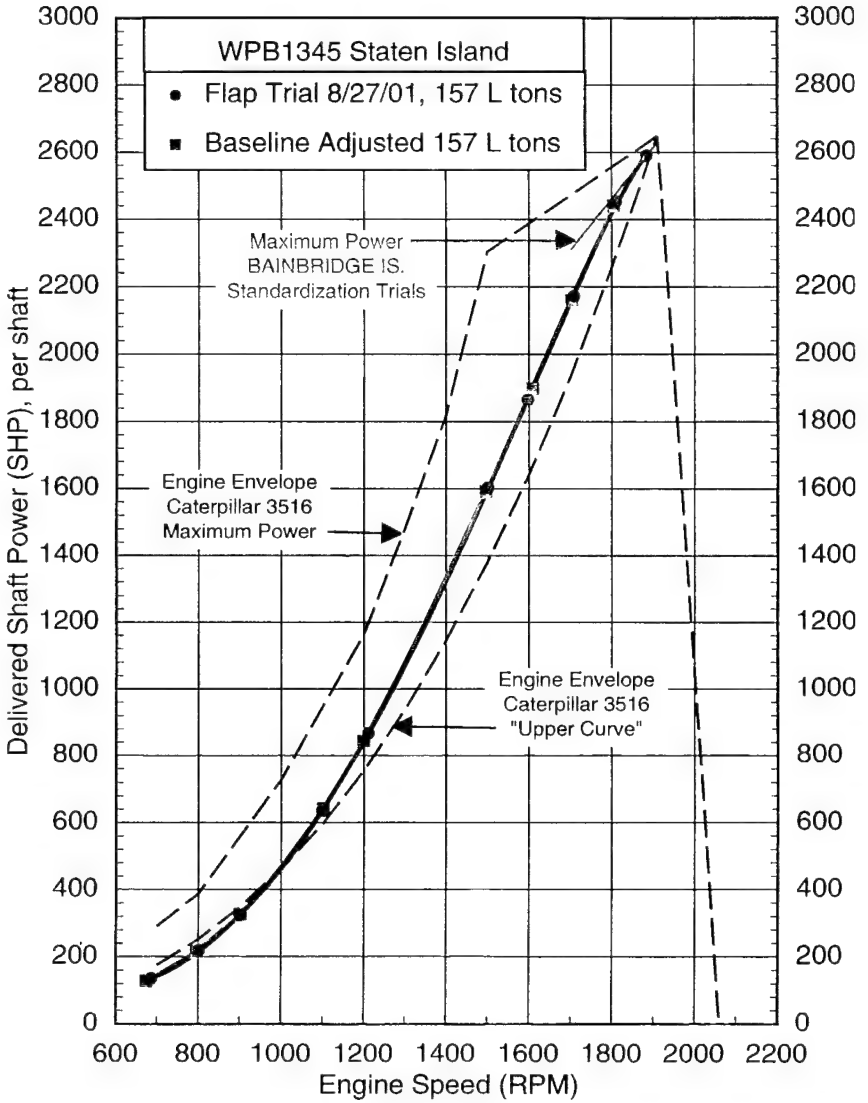


Fig. 6. WPB1345 *STATEN ISLAND* baseline and stern flap estimated powering, 157 L tons, with reference to main engine operating envelope

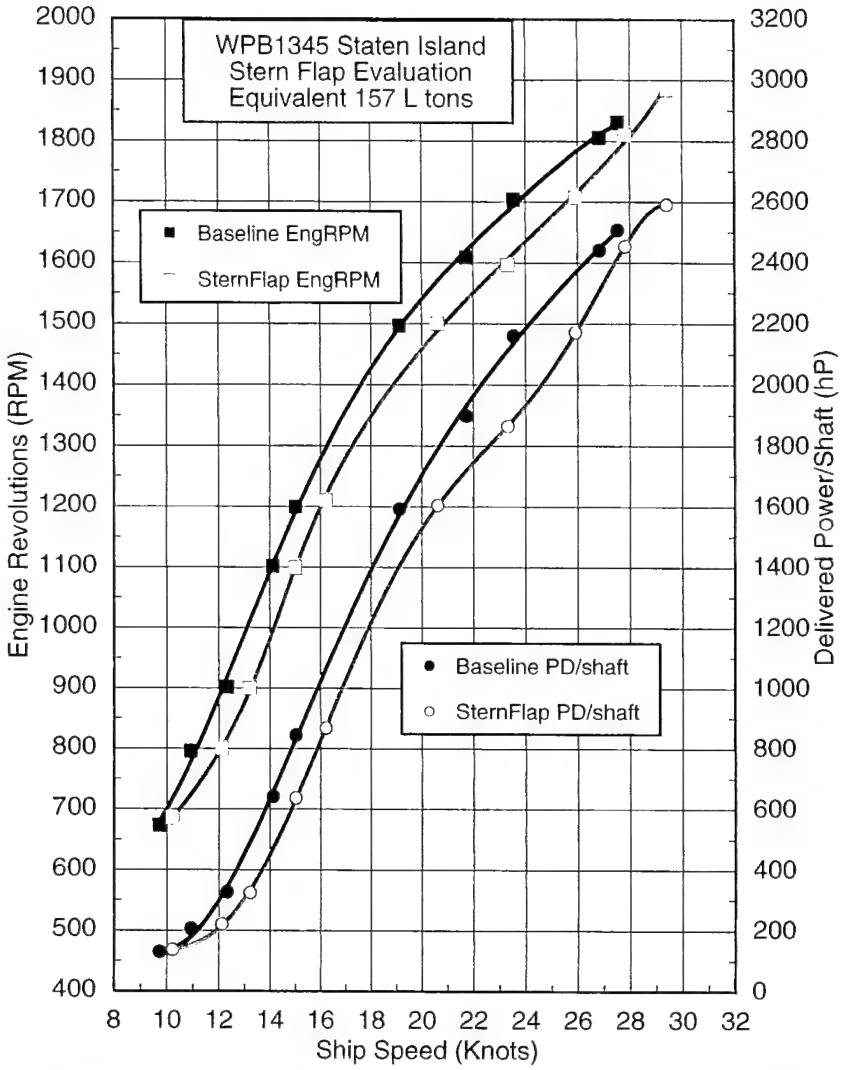


Fig. 7. WPB1345 *STATEN ISLAND* baseline and stern flap installed, estimated powering performances versus ship speed, 157 L tons

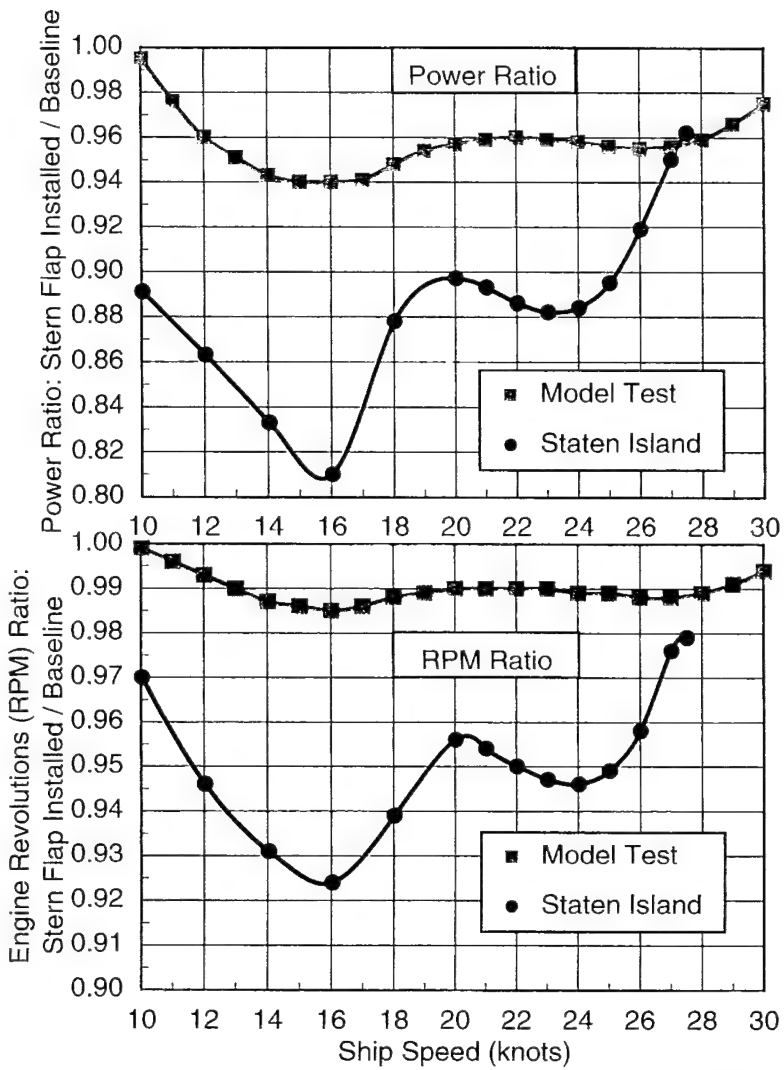


Fig. 8. Comparison of stern flap performance on WPB1345 *STATEN ISLAND* to that of the model-scale projection

Estimated Annual Fuel Savings

Engine specific fuel consumption (SFC) rates were determined at the shaft power levels indicated for the *STATEN ISLAND* baseline and stern flap configurations. Annual propulsion fuel consumption was estimated for a ship of the *ISLAND* Class by a summation of SFC rates, time-weighted by the average Class operational profile supplied by USCG (ELC-023). Annual underway operations were assumed to be 3000 hours at the single 157 L tons displacement. Time at full power was reduced for the stern flap configuration to account for the increase in top speed. The installation of a stern flap on a ship of the *ISLAND* Class, is estimated to reduce the annual fuel consumption by over 33,000 gallons (10.3%), when analyzed by the aforementioned technique, Table 7. The associated annual fuel cost savings (cost avoidance), using a fuel price of $1.50 per gallon, is over $50,000 dollars.

Table 7. USCG *ISLAND* Class (110 WPB) baseline and stern flap installed, estimated annual propulsion fuel consumption and savings

BASELINE (No Flap)					STERN FLAP INSTALLED					
	3000	Annual Underway hours				2981	Annual Underway hours			
Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission Operation (hours)	Annual Fuel Consumption (gal/yr)	Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission Operation (hours)	Annual Fuel Consumption (gal/yr)	Reduced Fuel Consumption (%)
12	510	31.6	1200	37,871	12	440	27.4	1200	32,862	-13.2
15	1593	89.1	750	66,858	15	1304	74.8	750	56,096	-16.1
18	2778	144.6	300	43,377	18	2439	128.9	300	38,658	-10.9
21	3687	189.1	150	28,371	21	3293	169.2	150	25,381	-10.5
23	4169	215.5	150	32,327	23	3675	188.5	150	28,278	-12.5
25	4575	240.0	150	36,005	25	4096	211.4	150	31,708	-11.9
27.5	5012	269.4	300	80,812	29.4	5180	281.6	281	79,007	-2.2
		Total Annual Fuel (gal/yr):		325,622			Total Annual Fuel (gal/yr):		291,989	
							Annual Fuel Savings (gal/yr):		33,633	-10.3%
							Fuel Cost Savings ($1.50/gal):		50,449	

The effects of the stern flap on fuel consumption must be considered as an initial rough order of magnitude (ROM) estimate. It is based upon stern flap evaluation speed trials on the *STATEN ISLAND*, with delivered power levels estimated from the *BAINBRIDGE ISLAND* standardization trials, and an average *ISLAND* Class operational profile. The data and estimates reflect operations in the twin shaftline propulsion mode only.

Ship Trim Effects

All stern flaps, independent of what size vessel they are used on, create a vertical lift force at the transom, and modify the pressure distribution under the afterbody. The developed forces can affect the trim angle substantially on high speed planing craft, such as the *ISLAND* Class. These hulls derive a significant portion of their total hull lift from dynamic forces, and one of the keys to minimizing resistance is often optimizing the hull trim angle. Fixed angle stern flap designs do generate a bow down trim moment and cause some loss of freeboard at the bow. Therefore, criteria defining the maximum allowable loss of freeboard is generally an input to these designs. A design criteria for the *ISLAND* Class stern flap was to limit the ship running trim modification to no greater than bow 1.0 degrees down (-1°), at all speeds.

Baseline and stern flap ship running trims on the *STATEN ISLAND*, measured during the speed trials, are presented in Figure 9. The ship trim criteria was satisfied throughout most of the speed range. The speed range of greatest power reduction, 12 to 18 knots, coincides with speeds where the stern flap appears to exceed the ship trim criteria.

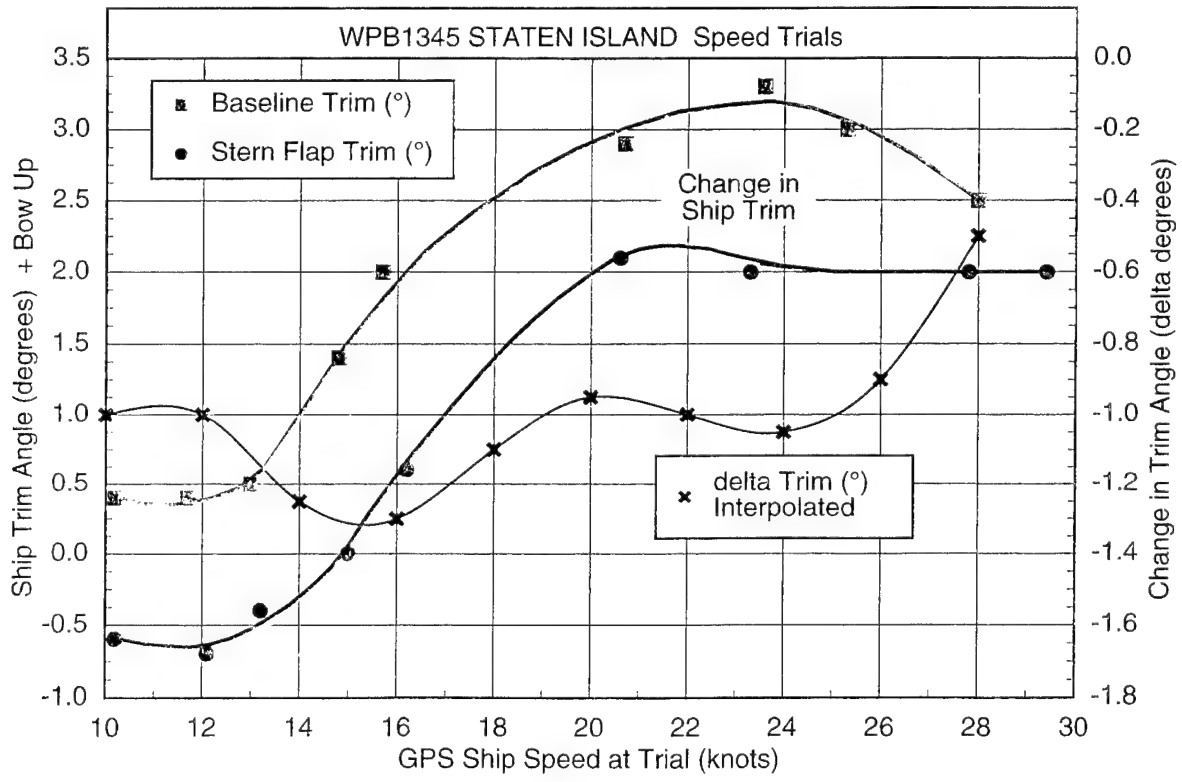


Fig. 9. WPB1345 *STATEN ISLAND* baseline and stern flap ship running trims

Modifications to Near-Field Transom Flow

Wave height, eddy-making, and turbulence, represent lost energy in the near-field transom flow of a vessel. At slow speeds, the transom (and flap if present) are fully wetted and the flow is said to be attached . Resistance is increased by the form drag of the immersed transom and by significant eddy-making. As speed increases, the transom becomes less submerged and the flow becomes transitional , periodically breaking free of the transom (and flap), and then rolling forward to wet them again. At a higher speed, there is clean flow separation or break-away from the transom (or flap). The speed at which this separation occurs is affected by factors which include ship displacement and trim, and transom design and depth of submergence. The specific design of a stern flap can have a significant effect on near-field flow. It has been shown that the flow exit velocity from the trailing edge of the stern flap is increased in comparison to the baseline transom, leading to a lower ship speed for clean flow separation.

Observations and photographs of the near-field transom flow were taken during the *STATEN ISLAND* speed trials, with and without the stern flap installed. The character of the transom flow was considerably altered by the stern flap over the entire tested speed range, Table 8.

The localized transom flows for the *STATEN ISLAND* baseline versus stern flap, at nominally 16 knots, are compared in Figure 10. The photographs present a view downward along the transom, to a range of about 12 ft (3.6 m) aft. The baseline exhibits attached transom flow, while with the stern flap installed the ship exhibits fully detached flow. The ship speed for transom flow separation was reduced to less than 15 knots with stern flap was installed, compared to slightly above 16 knots for the baseline. On the *STATEN ISLAND*, at the 16 knots, the stern flap exhibited the maximum powering reduction, as well as the largest modifications to both the near-field transom flow and the ship running trim.

The convergence wave, and wave system aft of convergence, appeared to be far less pronounced for stern flap than for the baseline, as depicted in the photographs of Figure 11, at nominally 25.5 knots. Whereas there appeared to be noticeable 2^{nd} and even 3^{rd} trailing (transverse) waves for the baseline case, there appeared to be only a much smaller 2^{nd} wave visible for the stern flap case. With the stern flap installed, the ridges along outboard edges of wake appeared less severe, and there also appeared to be a significant reduction in the amount of white-water and turbulence in the wake.

Table 8. WPB1345 *STATEN ISLAND* baseline and stern flap installed, observations of near-field transom flow

Condition No. (Nominal Engine RPM)	Baseline (No Flap)	Stern Flap Installed	Comments
1. (680)	10.2 knots. Fully attached across entire transom. Small convergence wave and a second observable trailing wave behind it.	10.2 knots. Fully attached across entire transom. However, upper surface of flap periodically becomes exposed for approx. 1/2 it's chord length, and then quickly is wetted again by roll-back.	
2. (800)	11.7 knots. Fully attached across entire transom, with very short periods of detachment along outboard 2-4 ft. Port side appears to show detachment more often.	12.1 knots. Fully attached. Aft 1/2 chord length of flap more often dry than wet, however, flow is not detaching from flap trailing edge.	
3. (900)	13.0 knots. Fully attached, with a greater height for convergence wave (approx. 1/3 height from water surface to weather deck). Crash-back is fairly severe. Strong ridges now formed along outboard edges of transom wake. Pronounced second trailing wave and third one also noticeable.	13.2 knots. Outboard edges of transom are in transition regime, and appear to be detached more often than attached. Aft 1/2 chord length of flap top surface again is often dry, however, volume of roll-back is greater as height of convergence wave appears greater.	Some transitional flow detachment appearing at lower speed for flap.
4. (1100)	14.8 knots. Fully attached along much of transom, however, approx. 3-4 ft of outboard edge breaks free fairly consistently. Flow is non-steady. Height of convergence wave now approx. 2/3 height from water surface to weather deck. Large 2nd and 3rd trailing waves. Strong ridges along outboard edges of transom wake.	15.0 knots. Flow detached along entire transom, however, still appears to be attached along trailing edge of flap even though outboard corners of flap are clear. Convergence wave becoming somewhat violent and very turbulent, but still of little height, as flap appears to suppress flow along ship centerline	Flow detached from transom with flap, attached for baseline transom. Actual flow detachment speed may be lower than 15.0 knots
5. (1200)	15.7 knots. Non-steady flow generally attached, but periodically detached - in transition. Roll-back from top of convergence wave crashes forward to within 1-2 ft of transom, and disrupts flow off bottom of transom. Height of convergence wave now approx. 2-4 ft above level of weather deck.	16.2 knots. Flow is clear of transom and flap. Convergence wave becoming larger even though flow is detached (approx. 1/3 height from water surface to weather deck), with a lot of unsteadiness and splash. Strong ridges now formed along outboard edges of transom wake. No second trailing wave noticeable yet.	Flow detached with flap, attached for baseline transom. Strong ridges and secondary waves appeared at much lower speeds for baseline transom.
6. (1500)	20.7 knots. Flow has detached from transom except for a very thin ridge at the centerline. Convergence wave much smaller, with no roll-back, but with a breaking ridge of turbulent flow approx. 2-4 ft high defining centerline of wake. Ridges along outboard edges of wake now very pronounced.	20.6 knots. Convergence wave still appears 1/3 the height to the weather deck with less turbulence and some splashing, and far removed from transom, 30-40 ft aft. Ridges along outboard edges of wake appear less severe than previous condition. The wake appears unusually flat behind convergence wave with no real secondary wave system.	Speed of flow detachment for baseline somewhere above 15.7 knots, but long before 20.7 knots.
7. (1600)	23.6 knots. Flow patterns similar to condition No. 6. Convergence now approx. 40 ft aft of transom, with central turbulent ridge extending 10 ft or so beyond that. Three very pronounced trailing waves. Outboard edges of wake appearing to become more turbulent, but with less defined ridges.	23.3 knots. Wake very similar to condition No. 6	Ridges along outboard edges of wake for flap appear less severe than baseline.
8. (1700)	25.3 knots. Similar flow as condition No. 7.	25.9 knots. Similar again to conditions Nos. 6 and 7.	Wave system aft of convergence wave far less pronounced for stern flap than for baseline.
9. (full power)	28.0 knots. Similar again to conditions Nos. 7 and 8. Breaking along wake outboard ridges creating some spray.	29.4 knots. Still unusually flat aft of convergence wave. Secondary wave system now observable trailing behind it.	

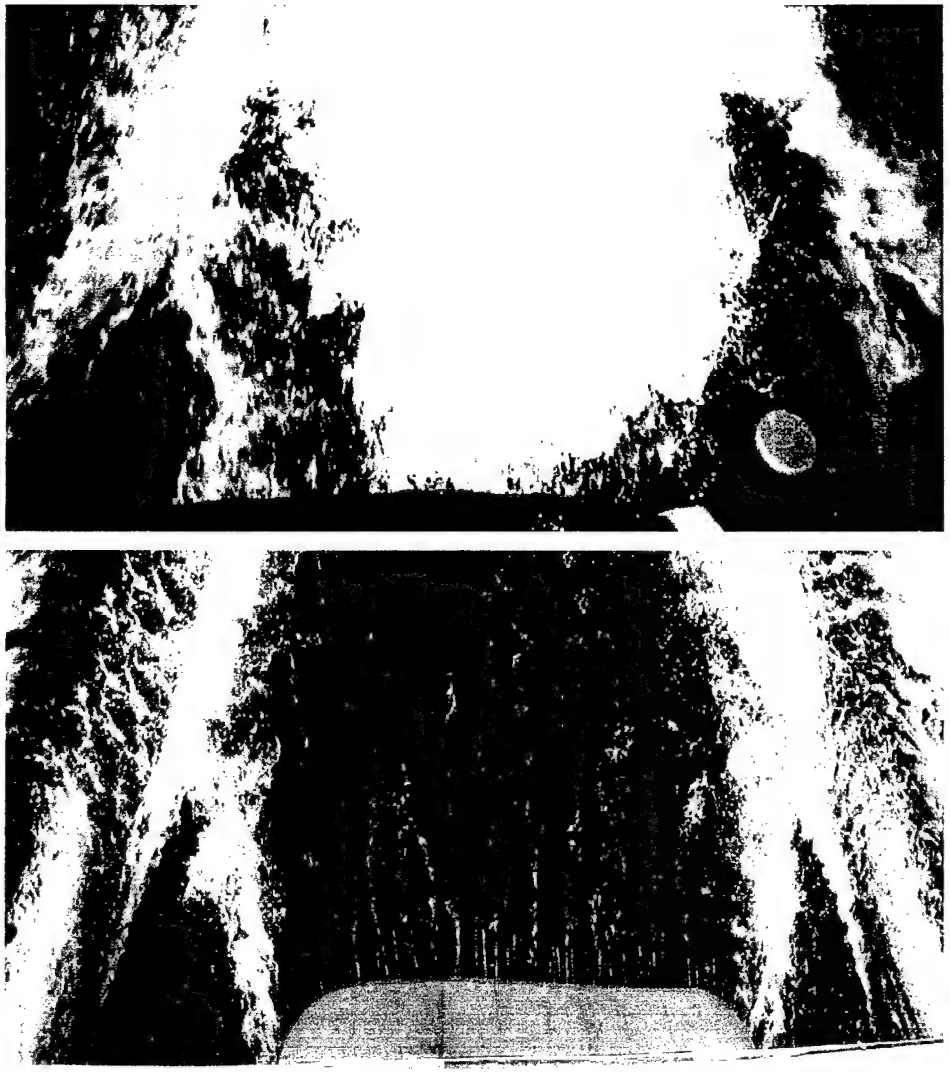


Fig. 10. Localized transom flow on WPB1345 *STATEN ISLAND*, baseline (upper) and stern flap installed (lower), nominal 16 knots

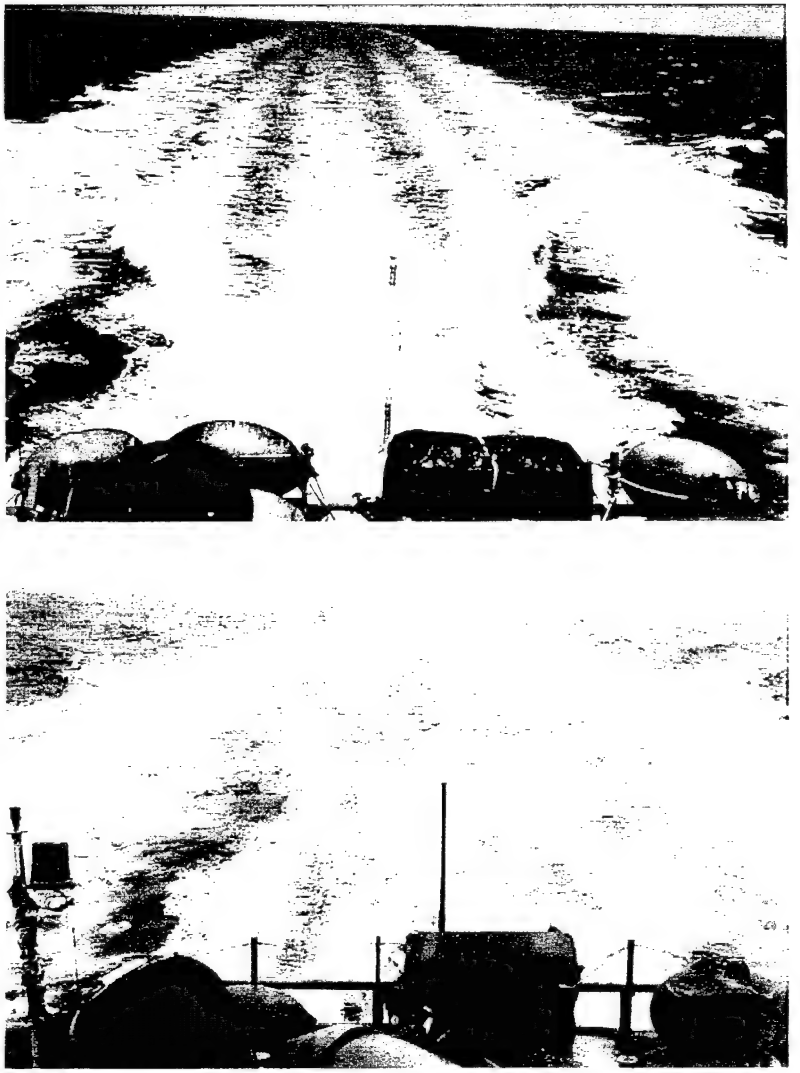


Fig. 11. Near-field transom waves on WPB1345 *STATEN ISLAND*, baseline (upper) and stern flap installed (lower), nominal 25.5 knots

CONCLUSIONS

Based upon at-sea trials conducted on the WPB1345 *STATEN ISLAND*, a stern flap installation on a ship of the USCG *ISLAND* Class (110 WPB), will have the following beneficial effects when compared to the baseline (no flap) configuration:

- The ship can maintain a significantly higher speed for the same engine RPM or developed shaft power, throughout the entire propulsion range of engine idle through full power.
- The stern flap allows for an additional 55 engine RPM and 168 hP to be developed at full power, which results in an increase in top speed of 1.9 knots.
- Comparison at equivalent ship speed, indicates a power reduction of 10.9% at a ship speed of 10 knots, increasing to a maximum of 19% at 16 knots, and maintaining a power reduction throughout the speed range.
- Estimated reduction in annual fuel consumption of over 33,000 gallons (10.3%). The associated annual fuel cost savings (cost avoidance) is over $50,000 dollars, using a fuel price of $1.50 per gallon.

At no point in the tested propulsion range did the stern flap installation induce a degradation in ship performance. The stern flap exhibited the maximum powering reduction, as well as the largest modifications to both the near-field transom flow and the ship running trim, at a ship speed of 16 knots.

ACKNOWLEDGMENTS

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APPENDIX A

WPB1343 *BAINBRIDGE ISLAND* STANDARDIZATION TRIALS RESULTS

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Table A1. WPB1343 *BAINBRIDGE ISLAND* standardization trials powering data

				Shaft RPM			Engine RPM			speed	Shaft Torque		Shaft Horse Power					
Run	Displ	LCG		Port	Stbd	Ave	Port	Stbd	Ave	Actual	Port	Stbd	Port	Stbd	Total	avg/shaft	Fuel	Trim
1/2	**137**	4.30	A	70	78	74	163	182	**173**	2.5	1590	2230	21.2	33.1	**54**	**27**	n/a	-1.3
3/4	**137**	4.30	A	112	110	111	261	257	**259**	4.1	3750	3480	80.0	72.9	**153**	**76**	n/a	-1.3
5/6	**137**	4.30	A	267	266	267	623	621	**622**	10.0	1847	1836	93.9	93.0	**187**	**93**	n/a	-1.3
7/8	**137**	4.30	A	355	352	354	828	821	**825**	12.7	3446	3188	232.9	213.7	**447**	**223**	n/a	-1.2
9/10	**137**	4.30	A	470	472	471	1097	1101	**1099**	15.9	6725	6378	601.8	573.2	**1175**	**587**	**64**	-0.2
11/12	**137**	4.30	A	551	546	549	1285	1274	**1280**	17.8	9522	8641	999.0	898.3	**1897**	**949**	**97**	0.6
13/14	**137**	4.30	A	645	647	646	1505	1509	**1507**	22.4	12215	11605	1500.1	1429.6	**2930**	**1465**	**142**	1.0
15/16	**137**	4.30	A	734	736	735	1712	1717	**1715**	26.4	14780	14174	2065.6	1986.3	**4052**	**2026**	**201**	1.1
17/18	**137**	4.30	A	808	817	813	1885	1906	**1896**	30.2	17009	16697	2616.7	2597.3	**5214**	**2607**	**276**	1.1
1/2	**137**	5.90	A	268	267	268	625	623	**624**	9.8	1938	1817	98.9	92.4	**191**	**96**	n/a	-0.6
3/4	**137**	5.90	A	355	359	357	828	838	**833**	12.6	3503	3443	236.8	235.3	**472**	**236**	n/a	-0.5
5/6	**137**	5.90	A	478	475	477	1115	1108	**1112**	15.4	6944	6675	632.0	603.7	**1236**	**618**	**67**	0.2
7/8	**137**	5.90	A	551	553	552	1285	1290	**1288**	18.0	9266	8992	972.1	946.8	**1919**	**959**	**103**	0.6
9/10	**137**	5.90	A	646	647	647	1507	1509	**1508**	22.3	12325	11345	1516.0	1397.6	**2914**	**1457**	**146**	1.0
11/12	**137**	5.90	A	734	734	734	1712	1712	**1712**	26.7	14756	13961	2062.2	1951.1	**4013**	**2007**	**199**	1.3
13/14	**137**	5.90	A	808	820	814	1885	1913	**1899**	30.8	16999	16670	2615.2	2602.6	**5218**	**2609**	**275**	1.5
1/2	**151**	5.09	A	275	275	275	642	642	**642**	10.0	2086	2054	109.2	107.5	**217**	**108**	n/a	-1.2
3/4	**151**	5.09	A	344	345	345	803	805	**804**	11.8	3346	3299	219.2	216.7	**436**	**218**	n/a	-1.0
5/6	**151**	5.09	A	472	469	471	1101	1094	**1098**	15.1	7132	6817	640.9	608.7	**1250**	**625**	**70**	-0.2
7/8	**151**	5.09	A	555	554	555	1295	1292	**1294**	17.5	9958	9605	1052.3	1013.1	**2065**	**1033**	**114**	0.8
9/10	**151**	5.09	A	646	648	647	1507	1512	**1509**	21.1	13201	12663	1623.7	1562.3	**3186**	**1593**	**163**	1.5
11/12	**151**	5.09	A	683	688	686	1593	1605	**1599**	22.9	14193	13609	1845.7	1782.7	**3628**	**1814**	**188**	1.7
13/14	**151**	5.09	A	728	729	729	1698	1701	**1700**	25.0	15657	14707	2170.2	2041.4	**4212**	**2106**	**215**	1.6
15/16	**151**	5.09	A	790	801	796	1843	1869	**1856**	29.2	16927	16687	2546.1	2544.9	**5091**	**2546**	**276**	1.3

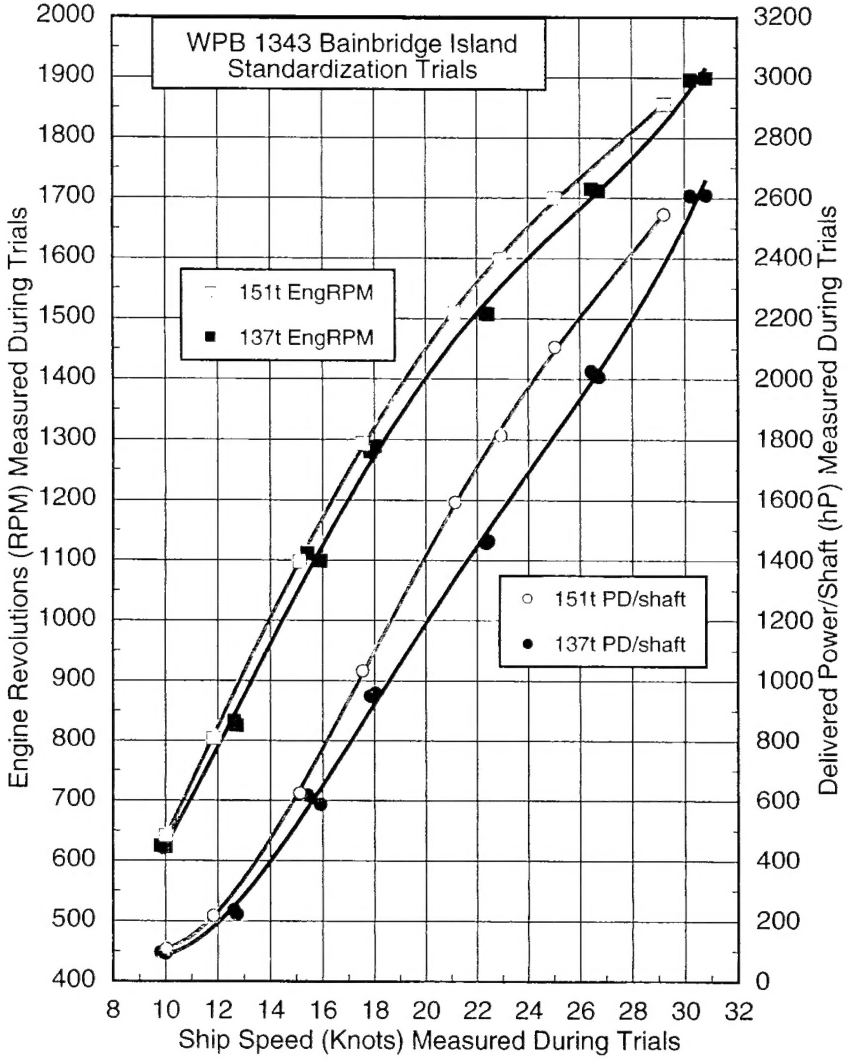

Fig. A1. WPB1343 *BAINBRIDGE ISLAND* standardization trials powering data versus ship speed

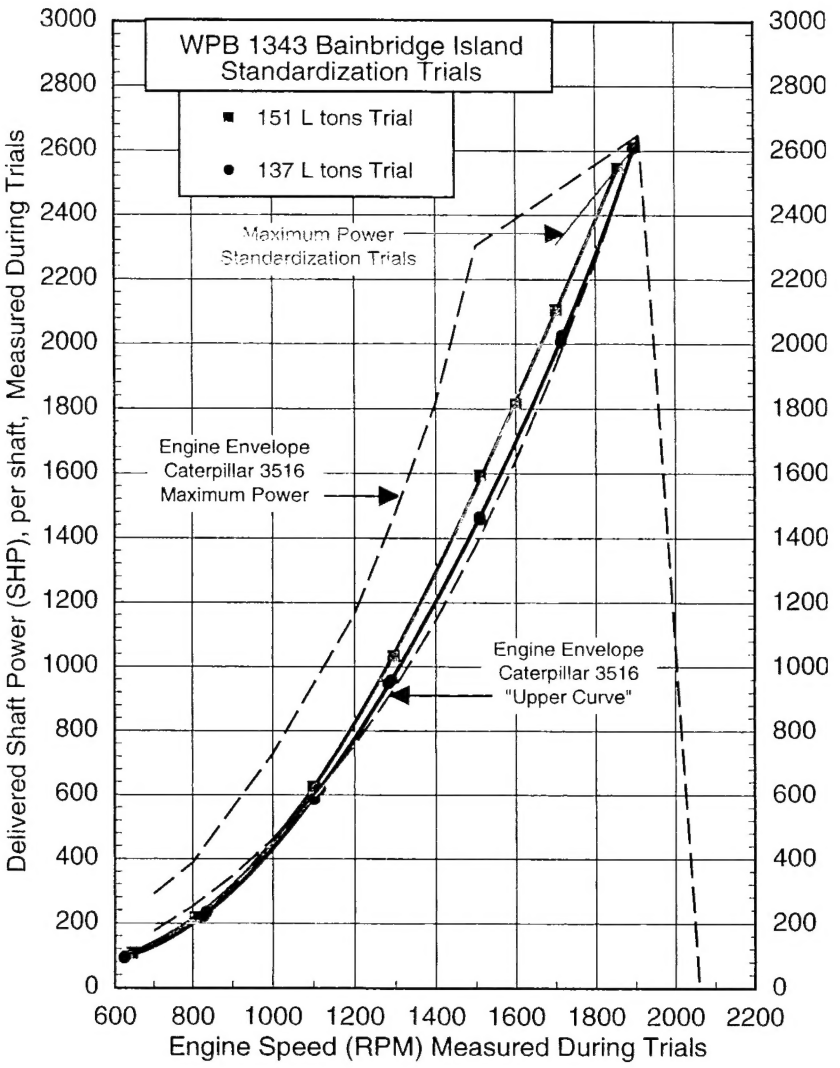

Fig A2. WPB1343 *BAINBRIDGE ISLAND* standardization trials powering data, with reference to main engine operating envelope

Table A2. WPB1345 *STATEN ISLAND* baseline and stern flap installed, speed trials data with shaft power estimated from standardization trials data, with estimated speed loss and power increase due to 20 L ton displacement adjustment

STATEN ISLAND Baseline (without Flap)			
Staten Island Trials 11 July 2001 **baseline,** 40% F/O at 137 L tons		Shaft Power from Stnd. Trials on Bainbridge Island at 137 L tons. Values at Staten Island Engine RPM.	
Engine RPM avg	GPS Speed (Knots)	PD/Shaft (hP)	Total PD (hP)
673	10.2	116	232
795	11.7	198	396
901	13.0	306	612
1101	14.8	598	1196
1199	15.7	778	1556
1496	20.7	1435	2870
1608	23.6	1721	3441
1703	25.3	1983	3967
1805	28.0	2295	4590

STATEN ISLAND with Stern Flap Installed			
Staten Island Trials 30 Aug 2001 **with flap,** 94% F/O at 157 L tons		Shaft Power from Stnd. Trials on Bainbridge Island Estimated at 157 L tons. Values at Staten Island Engine RPM.	
Engine RPM avg	GPS Speed (Knots)	PD/Shaft Est (hP)	Total PD Est (hP)
685	10.2	132	264
800	12.1	215	430
900	13.2	316	632
1099	15.0	620	1240
1210	16.2	845	1691
1500	20.6	1562	3124
1596	23.3	1817	3634
1707	25.9	2116	4231
1810	27.8	2391	4782
1885	29.4	2590	5180

STATEN ISLAND Baseline (without Flap)			
Staten Island Trials without Flap 137 L tons	Ship Speed and Shaft Power from Stnd. Trials on Bainbridge Island. Values at Staten Island Engine RPM. **Estimate at 157 L tons**		
Engine RPM avg	Est Speed (Knots)	PD/Shaft Est (hP)	Total PD Est (hP)
673	9.7	128	257
795	10.9	216	432
901	12.3	326	653
1101	14.1	641	1281
1199	15.0	843	1687
1496	19.1	1591	3181
1608	21.7	1897	3795
1703	23.5	2159	4318
1805	26.8	2440	4881
1830*	27.5	2506	5012

*Extrapolated to the maximum power level indicated in BAINBRIDGE ISLAND standardization trials data

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